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Multilevel tracking power supply for switch-mode audio power amplifiers

Niels E. Iversen¹, Vladan Lazarevic², Miroslav Vasic², Arnold Knott¹, Michael A.E. Andersen¹ and Jose A. Cobos²

¹Technical University of Denmark, Department of Electrical Engineering, 2800, Kgs. Lyngby, Denmark.

²Universidad Politecnica de Madrid, Centro de Electronica Industrial - CEI, Madrid, Spain.

Email: neiv@elektro.dtu.dk

Abstract—Switch-mode technology is the common choice for high efficiency audio power amplifiers. The dynamic nature of real audio reduces efficiency as less continuous output power can be achieved. Based on methods used for RF amplifiers this paper proposes to employ envelope tracking techniques to the power supply in order to improve efficiency. A 100 W prototype system was designed. Measured results show that systems employing envelope tracking can improve system efficiency from 2% to 12%, i.e. a factor of 6. The temperature rise is strongly reduced, especially for the switching power MOSFETs where it is halved from 100 °C to 50 °C.

I. INTRODUCTION

Switch-mode power audio amplifiers, also known as class-D amplifiers, have become the conventional choice for audio amplifications as they have excellent audio performance with very low distortion [1]–[3] and superior efficiency compared to linear amplifiers such as class-A and class-AB [4]. However the measurement technique for measuring the efficiency normally utilizes sine waves. Sine waves are fundamentally different from dynamic music signals and therefore do not represent real audio signals very well [5], [6]. Real audio signals are much more dynamic and have a high peak-to-rms ratio, also known as the Crest Factor (CF). Fig. 1 shows the amplitude distribution of 183 audio tracks provided by [6].

It is observed that amplitude distribution between audio and sine waves are fundamentally different and that real audio signals in fact are much more dynamic compared to sine waves. This highly dynamic nature of audio signals causes a degradation of efficiency as less continuous output power can be achieved. The dominant losses in the amplifier at low output power are switching losses which directly relate to the supply voltage level. Low efficiency is a challenge as it indicates an excessive loss within the amplifier which can cause thermal stress on power stage components, increase the size of required heat sink and act as a limiting factor for play back time in battery driven systems.

A similar challenge exists for Radio Frequency (RF) power amplifiers where highly dynamic radio signals cause low efficiency [7]–[9]. To overcome this challenge within RF power amplifiers several methods have been proposed including Envelope Tracking (ET) and Envelope Elimination and Restoration (EER) [10]–[13]. This work aims to apply a multilevel ET power supply to a 100 W class-D audio amplifier

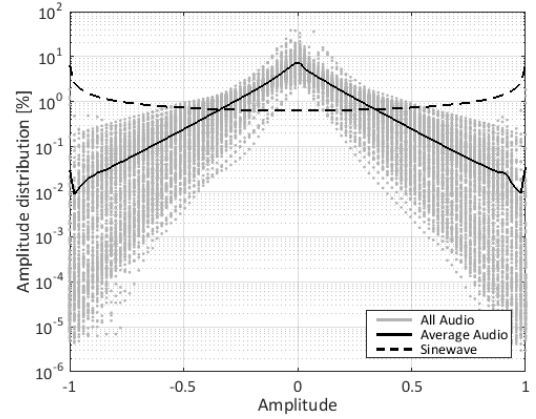


Fig. 1. Amplitude distribution of 183 audio tracks and sine wave [6].

in order to optimize efficiency and operating temperature when playing dynamic audio signals. This technique is not to be confused with conventionally class-H and class-G topologies as those are characterized by having a linear amplifier power stage, opposed to the switch-mode of class-D [14].

II. PROPOSED SOLUTION

This section presents the operating principle of the proposed ET power supply for the class-D amplifier along with relevant equations to estimate the expected impact on the system efficiency.

The core concept of the ET power supply is to supply the power amplifier with just the needed supply voltage so that the amplifier works correctly and does not produce excessive distortion due to clipping. For dynamic signals this will lower the switching losses significantly as they follow the simplified formula:

$$P_{sw} = \frac{1}{2} C_{ds} V_S^2 f_{sw} \quad (1)$$

Where C_{ds} is the parasitic capacitance of the amplifier switching device, V_S is the supply voltage and f_{sw} is the switching frequency. As seen from (1) the losses follow the supply voltage squared meaning that the magnitude of this voltage has great impact on the amount of switching losses.

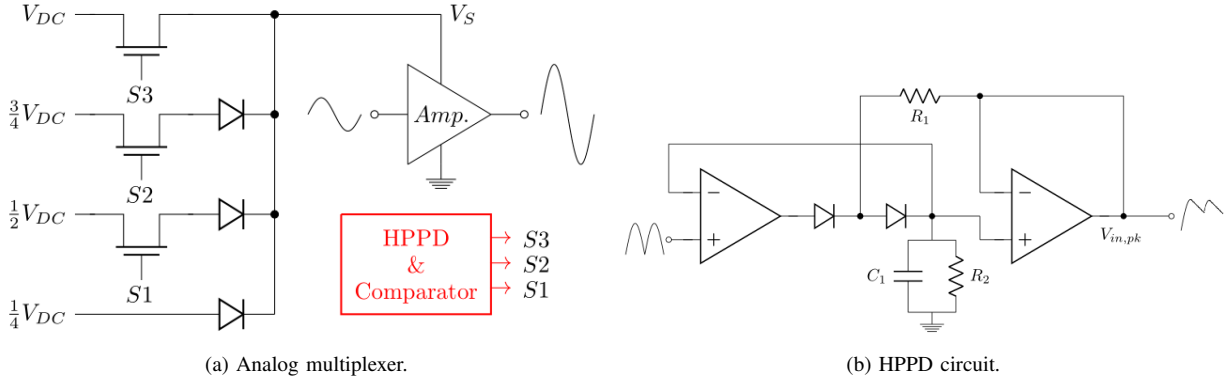


Fig. 2. Concept of proposed ET power supply consisting of a four level analog multiplexer and a High Precision Peak Detector (HPPD tracking circuit).

This paper proposes to implement the ET utilizing an analog multiplexer which selects the amplifier supply voltage, V_s , from four evenly spaced predefined voltage levels. This selection is performed based on an analysis of amplitude of the audio input which ensures that the amplified audio output generated by the amplifier is never clipped to the supply voltage. Fig. 2(a) shows a simplified schematic of the analog multiplexer. The control signals, $S1-S3$, is generated from an analog High Precision Peak Detection (HPPD) circuit, shown in Fig. 2(b), which tracks the rectified audio input signal. The output of the HPPD, $V_{in,pk}$, is fed to three comparators with hysteresis and individual thresholds, v_{th1-3} . The control signals, $S1-3$, are enabled when the audio input triggers these thresholds:

$$V_{in,pk} > v_{th1-3} \quad (2)$$

The speed of the tracking is set by the time constant formed by $C1$ and $R2$. The tracking speed does not need to very be fast to generate efficiency improvements as depicted in Fig. 3 which shows the predicted behaviour of the switching. Excessive switching in the multiplexer should be avoided as this will generate losses. Tracking speed is therefore a trade-off and a variable that can be optimized in future work. The

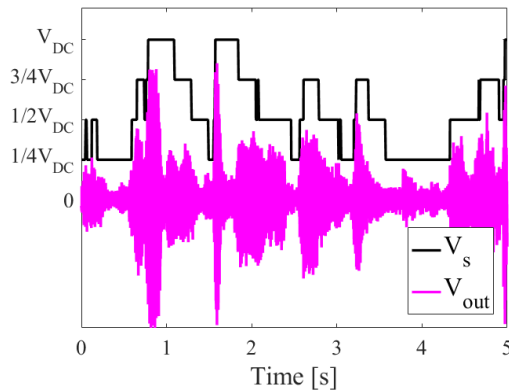


Fig. 3. Estimated Envelope Tracking (ET) power supply voltage, V_s , and amplifier output in case dynamic audio signal.

impact on efficiency the proposed system can be theorised by using a loss model, P_{loss} , based on common equations for switch- and conduction-losses available from previous work [15], [16].

$$P_{loss} = P_{gate} + P_{cond} + P_{sw} + P_{reverse} + P_{Lf} \quad (3)$$

Where P_{gate} is gate-, P_{cond} is conduction-, P_{sw} is switching-, $P_{reverse}$ is reverse body diode conduction- and P_{Lf} is filter-losses. The loss model should be evaluated for all desired operating points and supply voltage levels so that it can be formalized as a two dimensional array.

$$P_{loss} = \begin{pmatrix} p_{1,1} & p_{1,2} & \cdots & p_{1,d} \\ p_{2,1} & p_{2,2} & \cdots & p_{2,d} \\ \vdots & \vdots & \ddots & \vdots \\ p_{n,1} & p_{n,2} & \cdots & p_{n,d} \end{pmatrix} \quad (4)$$

where n is the voltage level and d is the operating point specifying a specific duty cycle. Equally the duty cycle distribution, ϕ , of the amplifier power stage can be formalized as:

$$\phi = \begin{pmatrix} \phi_{1,1} & \phi_{1,2} & \cdots & \phi_{1,d} \\ \phi_{2,1} & \phi_{2,2} & \cdots & \phi_{2,d} \\ \vdots & \vdots & \ddots & \vdots \\ \phi_{n,1} & \phi_{n,2} & \cdots & \phi_{n,d} \end{pmatrix} \quad (5)$$

The duty cycle distribution can be translated directly from the amplitude distribution of the audio signal, as long as the amplifier has a linear transfer function. The total loss can be described as the product between the loss model and the duty cycle distribution.

$$P_{tot} = \sum_{n=1}^N \kappa_n \cdot \phi_n \cdot P_{loss,n} \quad (6)$$

Where N is the total number of supply voltage levels and κ_n is an array containing the level distribution, i.e. the percentage spent on the n 'th supply voltage level.

$$\kappa = \begin{pmatrix} \kappa_1 \\ \kappa_2 \\ \vdots \\ \kappa_n \end{pmatrix} \quad (7)$$

III. IMPLEMENTATION

A prototype system was designed consisting of the ET power supply, equipped with analog multiplexer and the HPPD/comparator tracking circuit, and a 100 W switch-mode power amplifier, designed conventionally in accordance with [17]. Four fixed voltage levels was provided to the multiplexer circuit evenly spaced from 0 to 50 V, i.e. 12.5 V, 25 V, 37.5 V and 50 V. The time constant of the HPPD was set 12 seconds. The amplifier utilizes a synchronous buck topology in a full bridge configuration and has a gain of 32 dB, i.e. 40 V/V. Fig. 4(a) shows the simplified schematic of the amplifier power stage. The input signal range of the amplifier is ± 1 V. The thresholds, v_{th1-3} , of the HPPD/comparator tracking circuit were set to 0.2 V, 0.4 V and 0.6 V respectively, meaning that the multiplexer provides 50 V when the input signal exceeds ± 0.6 V. These thresholds were selected to ensure some headroom to the supply voltage levels thus avoiding significant distortion on the amplified audio signal. Fig. 4(b) shows the implemented system.

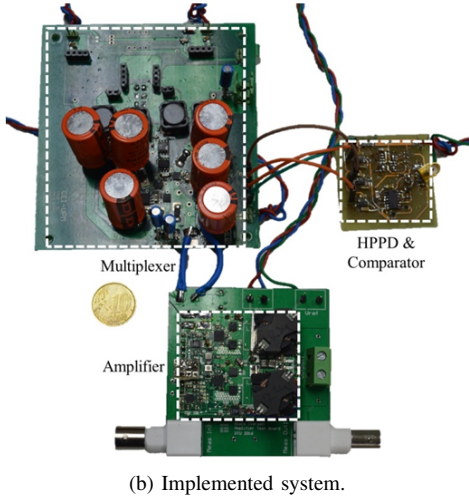
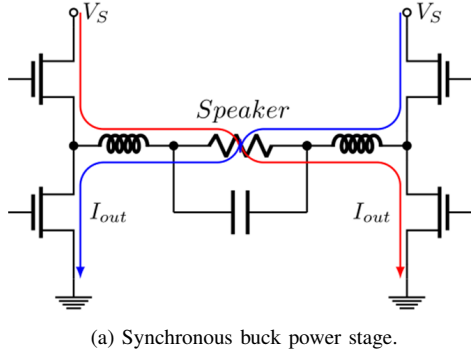


Fig. 4. Designed system consisting of audio amplifier using a synchronous buck topology and the proposed ET power supply consisting of analog multiplexer and HPPD/comparator tracking circuit.

IV. RESULTS

A series of measurements has been conducted in order to evaluate the impact on the system efficiency and its operating temperature. This includes measurements of system efficiency, using both conventional sine waves and dynamic audio signals

Fig. 7 shows the efficiency of the amplifier with and without the tracking power supply measured conventionally when driven by a sine wave. The input and output power is then measured using digital multi meters, Agilent 34401A. The measured efficiency is compared to predicted values obtained using (6). A good correlation between expectations and measurements is noticed. Especially for lower output powers. Moreover it is observed that the efficiency is greatly improved in the low power region when the tracking power supply is used. The low power efficiency is very important as the most probable power level lies in this range when playing real audio signals instead of sine waves. At 1 W the efficiency is improved from 30% to 65%. For high output levels the efficiency of the system with tracking supply has slightly lower efficiency as the additional circuitry in tracking power supply implementation add some losses. In addition to that the calculated predictions overestimates the efficiency 5 to 7% at higher output powers. This can be explained as a consequence of inaccurate modelling since the loss model does not account for the temperature and voltage dependent nature of the parasitic components of the switching device, e.g parasitic capacitance and on-resistance.

In order to evaluate the efficiency performance using real audio, three audio tracks from different genres have been selected. They have different dynamics as their peak-to-rms ratio, aka. Crest Factor, varies from 8.9 dB to 20.4 dB as seen in Table I.

In order to ensure that the tracks are perceived equally loud they have been loudness normalized in accordance with the EBU- R128 recommendation [18], [19]. For measurement reasons only the first twenty seconds of each track have been considered. Five loudness levels have been selected going from low volume up to clipping, i.e. maximum power. The

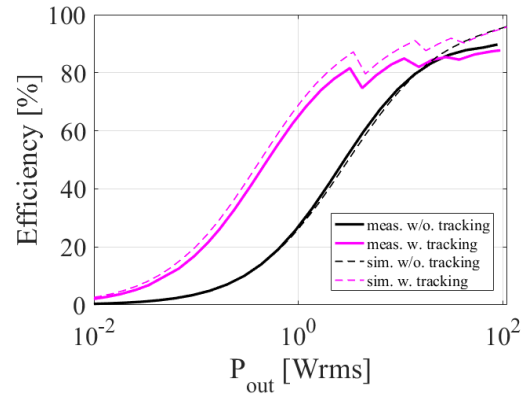


Fig. 5. Simulated and measured efficiencies with and without tracking.

corresponding rms output power can be found in Table II. A DPO3014 oscilloscope from Tektronix equipped with high precision current and voltage probes was used to capture the highly dynamic input and output voltages/currents. With a record length of 10 million points this oscilloscope ensures a sufficient sampling frequency when considering a 20 second audio signal. Fig. 6 shows the measured supply voltage as well as amplifier output playing Daft Punk - Get Lucky at loudness level 5. Though the tracking speed is slow it is clear that the proposed method ensures that supply voltage is vastly lowered for the majority of the audio signal. This will inevitably lower the losses in the power stage. Fig. 7(a) shows the measured and simulated efficiency of each track for the different loudness levels. The simulated results are based on the expected losses obtained using (6). There is a good correlation between the measured and expected results. It is observed that for all tracks and loudness levels the efficiency of the designed system is improved when the tracking power supply is enabled. Especially for low loudness levels the efficiency were improved. That is from 2 to 5% without tracking to 12 to 20% with tracking across the different tracks, i.e. up to a factor 6 improvement. In terms of power losses they were cut down from 2.5 W to only 0.5 W. The efficiency improvement is less significant for higher loudness levels but still a clear improvement is observed. That is from 32 to 53% without tracking to 59 to 76% with tracking across the different tracks. The highly dynamic jazz track, "Cant we be friends" marked by "o" in the figures, experiences the greatest efficiency improvement over all loudness levels. The influence of the tracking speed is also investigated. Fig. 7(b) shows the measured and simulated efficiency of the jazz track when the HPPD time constant is lowered from 12 to 3 seconds, resulting in a faster tracking. As expected the efficiency is increased for higher loudness levels but at the price of the signal quality as faster switching produces noise at the amplifier output.

The operating temperatures, in case of a 12 seconds HPPD time constant, were measured using a thermal camera. Fig.

8 shows the measured operating temperature of the audio amplifier with and without the tracking power supply in idle and for the selected audio tracks at loudness level 5. It is observed that in general the operating temperature is greatly reduced. Especially for the four switching MOSFETs

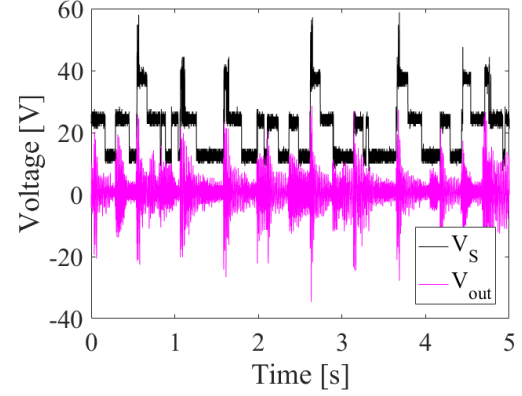
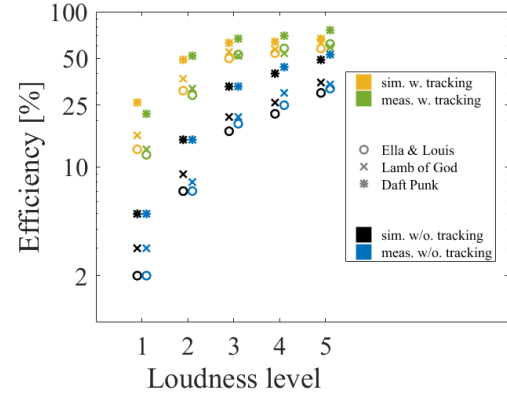
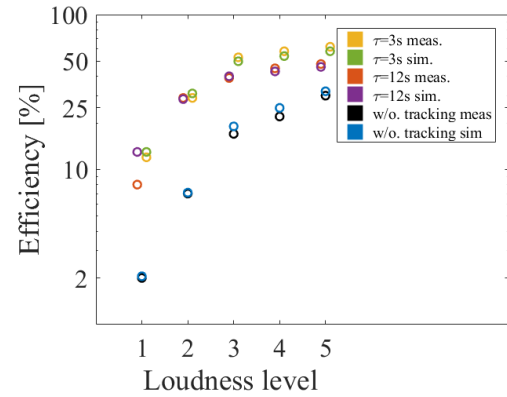


Fig. 6. Multilevel supply voltage and amplifier output in case of Daft Punk Get Lucky.



(a) Efficiency of implemented system.



(b) Impact from faster tracking.

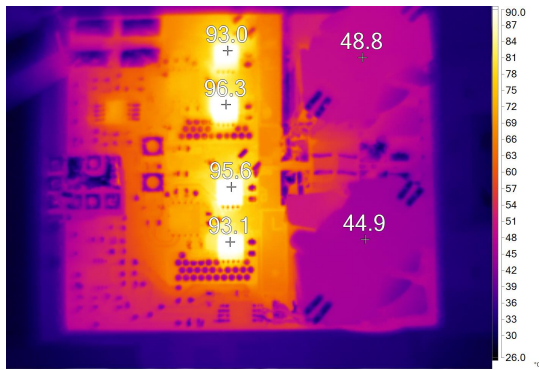
Fig. 7. Simulated and measured efficiencies for first 20 seconds of audio tracks. The corresponding output power for each track and loudness level is shown in Table II.

TABLE I
CREST FACTORS OF SELECTED AUDIO TRACKS.

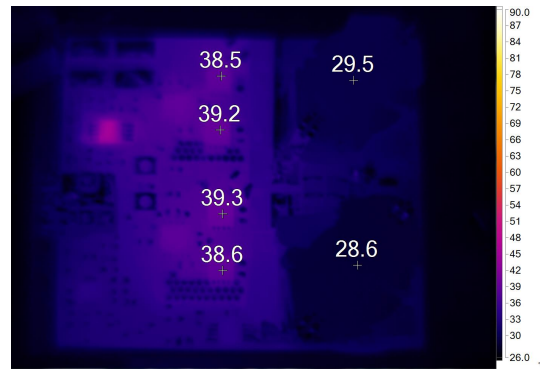
	Name	Artist	Genre	CF
1	Can't We Be Friends	Ella & Louis	Jazz	20.4 dB
2	Redneck	Lamb of God	Metal	8.9 dB
3	Get Lucky	Daft Punk	Pop	13.0 dB

TABLE II
CORRESPONDING OUTPUT POWER FOR DIFFERENT LOUDNESS LEVELS.

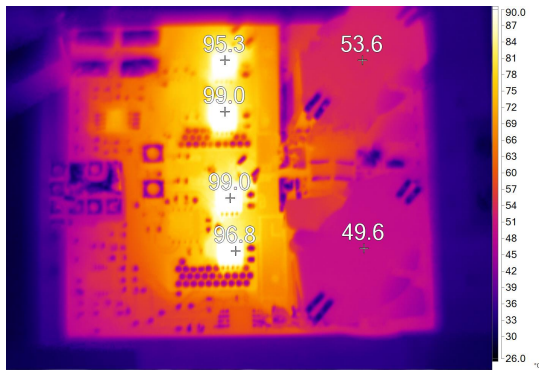
Loudness level vs. output power					
Loudness level	1	2	3	4	5
First 20 seconds					
Ella & Louis	0.06 W	0.20 W	0.56 W	0.80 W	1.20 W
Lamb of God	0.08 W	0.25 W	0.71 W	1.00 W	1.50 W
Daft Punk	0.14 W	0.47 W	1.34 W	1.90 W	2.80 W
Full track					
Ella & Louis	0.10 W	0.33 W	0.93 W	1.3 W	1.96 W
Lamb of God	0.14 W	0.46 W	1.32 W	1.86 W	2.77 W
Daft Punk	0.18 W	0.59 W	1.69 W	2.38 W	3.56 W



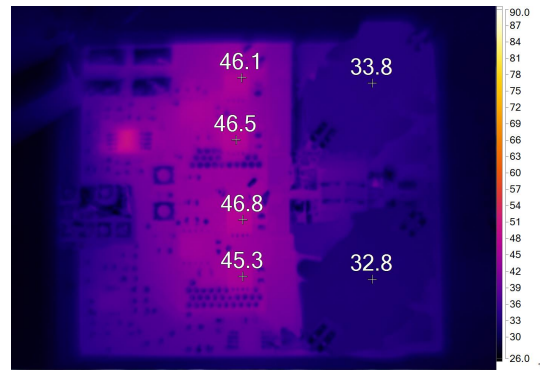
(a) Idle - Without tracking.



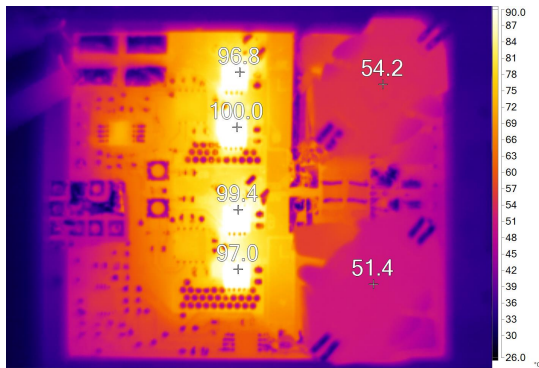
(b) Idle - With tracking.



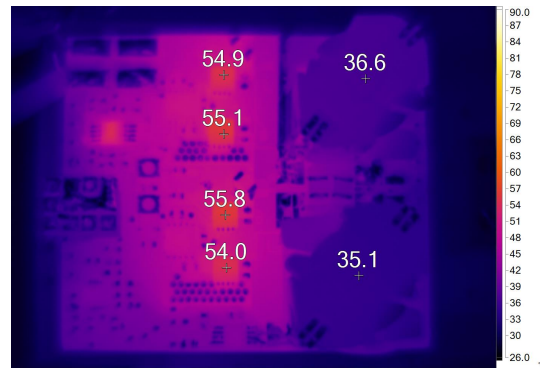
(c) Ella & Louis - Without tracking.



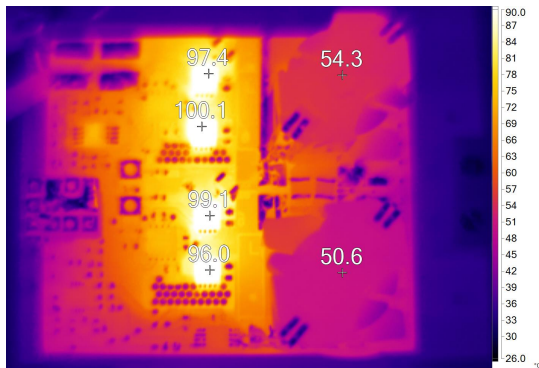
(d) Ella & Louis - With tracking.



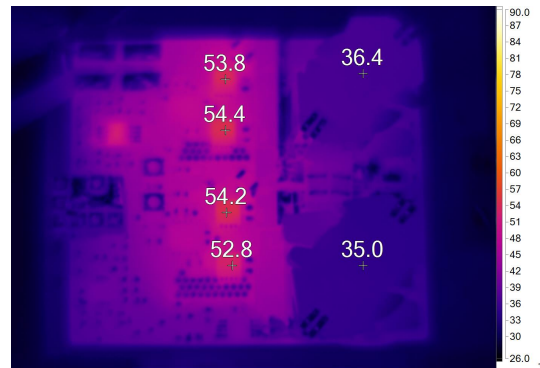
(e) Lamb of God - Without tracking.



(f) Lamb of God - With tracking.



(g) Daft Punk - Without tracking.



(h) Daft Punk - With tracking.

Fig. 8. Measured temperatures of amplifier with- and with-out tracking at loudness level 5.

in the amplifier power stage where the temperature is halved from approximately 100 °C to 50 °C across all tracks. In the same manner the inductor temperature is reduced from approximately 50 °C to 35 °C. A summary of the measured operating temperatures is presented in Table III. This great reduction in MOSFET operating temperature is obtained as the switching losses are greatly reduced. The reduction of the temperature in the filter inductor is related to a smaller ripple current when the supply voltage is low thus causing less AC winding- and core-losses.

Finally crude listening test where performed to evaluate audio quality when the tracking power supply is enabled. From these listening sessions it is clear that the level-shifting, introduced by the tracking power supply, generates undesired audible clicks and therefore it has a negative effect on the audio performance. This can be solve either by having a higher power supply rejection ratio in the amplifier or a lower slew rate in the analog multiplexer. It remains future work to overcome this challenge.

V. CONCLUSION

The work presented in this paper proposes that tracking power supplies can provide similar efficiency improvements when applied to switch-mode power audio amplifiers as shown for RF amplifiers in previous work. To demonstrate this hypothesis a prototype system was designed consisting of a 100 W power audio amplifier and a tracking power supply based on an analog multiplexer. Measured results show that systems using a tracking power supply achieve significantly higher efficiencies. Especially for low loudness levels the efficiency were improved up to a factor of 6. That is from approximately 2 to 5% without tracking to 12 to 20% with tracking across different music genres. In terms of power losses they were cut down from approximately 2.5 W to only 0.5 W. In addition to that it is observed that the amplifier operating temperature is strongly reduced, especially for the switching power MOSFETs where it has been halved from 100 °C to 50 °C. Moreover measured results show that the efficiency can be further improved for high loudness levels, by increasing the tracking speed.

VI. FUTURE WORK

Future work includes an implementation using a switch-cap circuit to generate the fixed voltage levels as proposed in [9]. In addition to this the control signals, $S1 - S3$, may be implemented on an audio DSP instead of the HPPD/comparator

circuit, as audio DSPs is a typical component in audio systems [21]. Finally good audio quality must be ensured. That means no audible artefacts on the amplified audio signal. This can be achieved either by having high power supply rejection ratio in the amplifier or a lower slew rate in the analog multiplexer, meaning that the jump in supply voltage level happens slower.

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TABLE III
SUMMARY OF TEMPERATURE MEASUREMENTS SHOWN IN FIG. 8

Mean temperatures				
Input	w/o. tracking		w. tracking	
	MOSFETs	Ind.	MOSFETs	Ind.
Idle	94.5 C°	46.9 C°	37.2 C°	29.1 C°
Ella & Louis	97.5 C°	51.6 C°	46.2 C°	33.3 C°
Lamb of God	98.3 C°	52.8 C°	55.0 C°	35.9 C°
Daft Punk	98.2 C°	52.5 C°	53.8 C°	35.7 C°